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RELATIVISTIC PARTICLES AND GAMMA-RAYS IN QUASARS AND ACTIVE GALACTIC NUCLEI

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I. ABSTRACT

A model for a class of quasars and active galactic nuclei is described in which a shock around a massive black hole randomizes the infall kinetic energy of spherically accreting matter producing a non-thermal spectrum of high energy protons. These protons may be responsible for the secondary production (via π^\pm decay) of the radio emitting high energy electrons and also of high energy γ -rays (via π^0 decay and inverse Compton interactions of the electrons). The correlation between radio and γ -ray emission implied by the model is in good agreement with observations of 3C273. Observation of the flux of high energy neutrinos from quasars may provide a test for the model.

II. INTRODUCTION

Accretion onto compact objects has long been considered as an energy source to power quasars (Lynden Bell 1969) and is thought to be the only mechanism capable of satisfying their enormous power requirements. Radio, X-ray and γ -ray observations show that some quasars and active galactic nuclei emit roughly the same energy per decade (i.e. per logarithmic energy interval, $d \log_{10} E$) from radio to X-ray energies and, in the case of 3C273, to γ -ray energies. Relativistic particles required to account for the observed radio, X and γ -ray emission may result from acceleration in shocks via a first-order acceleration mechanism (Protheroe and Kazanas, 1982). This mechanism, efficient (up to 98 percent; Axford 1981) in transforming directed kinetic energy into

relativistic particle energy, has already been proposed to account for the observed cosmic ray spectrum (Bell 1978a, b; Axford, Leer and Skadron, 1977; Blandford and Ostriker, 1978; Cowsik and Lee, 1981). For strong shocks, this process naturally produces a power law spectrum with index -2 , i.e., equal energy per decade. The nuclear interaction of protons accelerated by this process results in production of γ -rays and secondary electrons responsible for synchrotron and inverse Compton emission.

III. PARTICLE ACCELERATION AND RADIATION PROCESSES

A shock around a massive black hole may serve both to randomize the infall kinetic energy of the gas and also to produce a non-thermal distribution of high energy (relativistic) protons. Because of the high photon energy densities ($> 200 \text{ erg cm}^{-3}$ for 3C273 if the source region has dimensions less than 10^{17} cm) and the magnetic fields present, electrons will suffer severe Compton and synchrotron losses, effectively prohibiting their direct acceleration. We shall, therefore, consider here secondary electrons resulting from nuclear collisions of the non-thermal proton distribution via pion production. Relativistic protons with kinetic energies much greater than the gravitational potential of the black hole, do not readily fall into it. They can provide sufficient pressure to satisfy the jump conditions across the shock, the position of the shock being then fixed by the balance between inflection and removal of relativistic protons behind it. Gamma-ray production via π^0 decay and via inverse Compton scattering of the relativistic electrons are considered.

The spectrum of protons accelerated by the shock has a power law momentum dependence, i.e., $Q(p) = K p^{-\Gamma}$ (protons $\text{GeV}^{-1} \text{ c s}^{-1}$). For a strong shock (compression ratio $= \Gamma + 1$), $\Gamma = 2$. The relativistic protons are assumed to be trapped within a radius comparable to the shock radius by magnetic fields which are tied to the infalling matter. The matter density in this region is assumed to be sufficiently high that the relativistic protons are depleted mainly by nuclear interactions with consequent pion production.

The production spectrum of γ -rays, $Q_\gamma(E)$, resulting from π^0 decay (Stecker 1971) has been calculated and is plotted in Figure 1(a) where it is normalized to the proton production spectrum at high energies, $K E^{-2}$. The production spectrum of secondary electrons $Q_e(E)$ (e^+e^-) from $\pi^+-\mu^-e$ decay has been calculated and is also plotted in Figure 1(a). Above $\sim 1 \text{ GeV}$, $Q_e(E) = Q_{\gamma}(E) = 0.15 Q_p(E)$ for $\Gamma = 2$; the remaining energy goes into neutrino production, $Q_\nu(E) = 0.7 Q_\gamma(E)$. To obtain the absolute normalization of $Q_p(E)$ for 3C273, we shall consider its observed radio-optical spectrum. If we attribute the flat ($F_\nu \sim \nu^{-1}$) part of the spectrum from the radio to the visible to synchrotron

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radiation, then the total electron luminosity, $2.3E^2 Q_e^{\text{tot}}(E)$, is approximately $2(1 + \alpha)/\alpha$ times the synchrotron luminosity, where α is the ratio of energy densities in the magnetic and radiation fields. $Q_e^{\text{tot}}(E)$ is the rate of production of electrons at high energies (electrons $\text{erg}^{-1} \text{s}^{-1}$) and is equal to $Q_e(E)$ plus the production spectrum of electrons and positrons resulting from photon-photon pair production interactions.

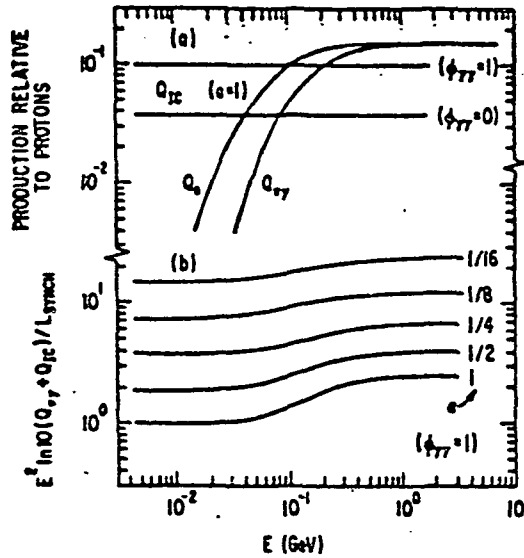


Fig. 1: (a) Production spectra of electrons (Q_e), γ -rays from π^0 decay ($Q_{\pi^0\gamma}$) and γ -rays from inverse Compton interactions for $\alpha = 1$ (Q_{IC}) relative to the production rate of protons. Separate curves are given for Q_{IC} corresponding to $\phi_{YY} = 0$ and 1. (b) Total production rate of γ -rays for $\phi_{YY} = 1$ relative to the radio synchrotron luminosity for different values of α .

Assuming the electrons are trapped within the shock radius, R , and lose energy by inverse Compton and synchrotron radiation, the ambient spectrum of electrons, $N_e(E)$, is determined by

$$Q_e^{\text{tot}}(E) - \frac{d}{dE} \left\{ \frac{dE}{dt} N_e(E) \right\} = 0, \quad (1)$$

where, $dE/dt = -3.97 \times 10^{-2} (1 + \alpha) U_{\text{rad}} E^2 \text{ erg s}^{-1}$ and U_{rad} is the radiation energy density, taken to be $L_{\text{Total}}/\pi R^2 c$. For inverse Compton interactions, the γ -ray production rate is,

$$Q_{IC}(E) = \int_0^\infty N_e(E') \left\{ \int_{E/4\gamma}^E n_{\text{ph}}(\epsilon) \sigma(E, \epsilon, E') d\epsilon \right\} dE' \quad (2)$$

where $\gamma = E'/mc^2$, $n_{\text{ph}}(\epsilon)$ is the number density of photons in the radiation field (photons $\text{cm}^{-3} \text{ erg}^{-1}$), and $\sigma(E, \epsilon, E')$ is the differential cross section for an inverse Compton interaction in which an electron of energy E' interacts with a photon of energy ϵ , boosting its energy to E .

We have solved equation (1) for the two extreme cases where the source is optically thin ($\phi_{YY} = 0$) or thick ($\phi_{YY} = 1$) to γ -ray pair production interactions. (ϕ_{YY} is the probability that a γ -ray will annihilate with an X-ray photon producing an electron-

positron pair). The resulting inverse Compton γ -ray production spectra are plotted in Figure 1(a) for these two cases and $\alpha = 1$.

IV. GAMMA-RAY SPECTRUM OF 3C273

The observed γ -ray spectrum will be the total γ -ray production spectrum ($Q_{\gamma\gamma} + Q_{IC}$) modified by photon-photon pair production interactions. To calculate this effect, we must know the radius of the object, R . We shall obtain R from the frequency below which the synchrotron radiation becomes optically thick to synchrotron self absorption. Solving equation (1), the number density of relativistic electrons of energy E within the source is $n(E) = n_0 E^{-3}$, where $n_0 = (4.9 \times 10^{11} L_{\text{synch}}) / (\alpha L_{\text{Total}} R)$. For this spectrum, the frequency below which synchrotron self absorption becomes important, ν_1 , is given by Pacholczyk (1970),

$$\nu_1 = 2C_1(SC_6)^{2/7} n_0^{2/7} B_1^{5/7} \quad (3)$$

where B_1 is the component of magnetic field perpendicular to the line of sight ($B_1 = .8\langle B \rangle$), $S = 1.3 R$ is the average distance through the source, C_1 and C_6 are constants. The synchrotron self absorption does not result in a sharp spectral break in 3C273. This may be understood in terms of non-uniform radial distributions of electron density and magnetic field (Condon and Dressel, 1973). ν_1 appears to be in the range $3 \times 10^{11} - 10^{12}$ Hz for 3C273, hence we find $R\alpha^{-1/8} = 5 \times 10^{17} - 10^{17}$ cm and $\langle B \rangle \alpha^{-2/5} = 14 - 75$ gauss.

We can now use these estimates of the radius to obtain the photon density in the X-ray region from the observed X-ray flux data and hence the effects of pair production interactions on the γ -ray spectrum. The optical depth to γ -rays of energy E is $\tau(E) = S \int n_{\text{ph}}(\epsilon) \sigma(E, \epsilon) d\epsilon$ where $n_{\text{ph}}(\epsilon)$ is the number density of photons of energy ϵ , and $\sigma(E, \epsilon)$ is the differential cross section for pair production interactions of γ -rays of energy E with photons of energy ϵ . (Heitler, 1954). We have used X-ray data of Worrall et al. (1979) and Primi et al. (1979) and the assumed radius to obtain $n_{\text{ph}}(\epsilon)$.

The energy spectrum of γ -rays escaping from the source is then down by a factor, $(1 - e^{-\tau})/\tau$, from that at production. For 3C273 this factor is plotted as a function of energy in Figure 2(a) for various assumed radii. We see that the source is optically thick to γ -rays above ~ 100 MeV for radii in the range obtained earlier. We have therefore plotted in figure 1(b) the γ -ray spectrum at production ($Q_{\gamma\gamma} + Q_{IC}$) for $\phi_{\gamma\gamma} = 1$ and for values of α ranging from 1 to 1/16. The observed γ -ray luminosity (Hermesen et al., 1981) is compared in Figure 2(b) with our prediction taking into account photon-photon absorption and is found

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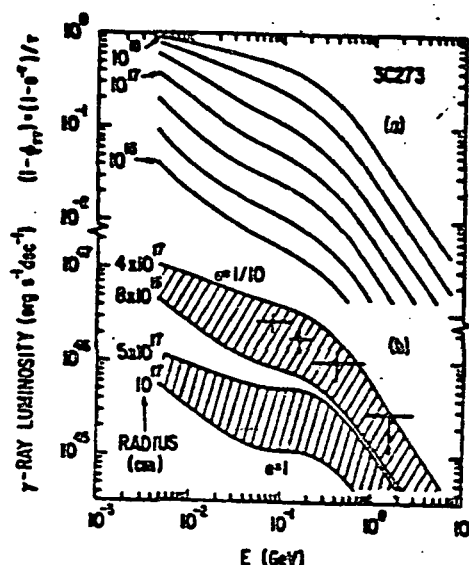


Fig. 2: (a) Reduction factor applied to predicted optically thin γ -ray spectra for 3C273 for various assumed radii in order to obtain the expected γ -ray emission. (b) Gamma-ray luminosity of 3C273 based on the observed spectrum (Hermesen et al., 1981) compared with the luminosity predicted for $\alpha = 1/10$ and for the range of radii obtained as described in the text.

to be in good agreement with the prediction for $\alpha = 0.1$ and $R \sim 10^{17}$ cm. This radius is consistent with that we obtained earlier by considering the radio spectrum some 12 decades lower in energy.

V. CONCLUSIONS

We have discussed a model for a class of quasars and active galactic nuclei, gauged to 3C273. It focuses on the high energy particles in these objects which are responsible for the radio and γ -ray emission and predicts a correlation between these two extreme parts of the spectrum which appears to be in good agreement with observations of 3C273. The model provides estimates of the central source radius and its magnetic field. If the total observed luminosity ($L_{\text{total}} = 2 \times 10^{47} \text{ erg s}^{-1}$) is due to gravitational energy release at the surface of the shock, and the relativistic particle pressure balances the accretion ram pressure ρv^2 , then the radius inferred above implies a mass of $\sim 10^{10} M_{\odot}$, and an accretion rate of $\sim 10^2 M_{\odot} \text{ yr}^{-1}$.

The estimated radius is compatible with variability time scales of the order of several months which have been observed (Worrall et al. 1979). Variability reported on much shorter time scales (~ 1 day) (Marshall, Warwick and Pounds, 1981) would clearly be incompatible with our model. However, the statistical significance of these data is low and they may also be compatible with a much longer time scale variability. It is important to point out here that a radius of ~ 1 light day would render 3C273 completely opaque to γ -rays of energies greater than a few MeV, contrary to observation.

Pair production by high energy γ -rays and production of electrons by pion decay throughout the source volume avoids the Compton Catastrophe (Hoyle, Burbidge and Sargent, 1966) and allows a higher energy density in the radiation field than in the magnetic field (i.e. $\alpha < 1$). The model also provides a situation similar to that considered in the literature for the formation of jets (Smith et al. 1980), i.e., a hot gas (the relativistic particles) underneath a cold gas (the infalling cold gas).

Based on this model, one would expect emission of high energy γ -rays from other quasars and active galactic nuclei. So far, Cen A is the only other source detected in high energy γ -rays (Grindlay et al., 1975). The observed flux is compatible with that predicted by a simple model for Cen A (Kazanas and Protheroe 1982) similar to that discussed here for 3C273.

Finally, the model predicts a higher flux of high energy neutrinos than in models where electrons are directly accelerated. We predict a flux of $\sim 1.4 \times 10^{-10} \times (1+2\alpha)$ neutrinos (all types) $\text{cm}^{-2} \text{s}^{-1}$ above 1 TeV for 3C273. This may be within the detection capability of the proposed DUMAND neutrino telescope (Stenger, 1981) and thus may provide a test of the model.

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